# Recent Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics


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***Abstract*-- We present data on the vulnerability of a variety of candidate spacecraft electronics to proton and heavy ion induced single event effects and proton-induced damage. Devices tested include optoelectronics, digital, analog, linear bipolar, hybrid devices, Analog-to-Digital Converters (ADCs), Digital-to-Analog Converters (DACs), and DC-DC converters, among others.**


## I. INTRODUCTION

As spacecraft designers use increasing numbers of commercial and emerging technology devices to meet stringent performance, economic and schedule requirements, ground-based testing of such devices for susceptibility to single event effects (SEE) and proton-induced damage has assumed ever greater importance.

The studies discussed here were undertaken to establish the sensitivities of candidate spacecraft electronics to heavy ion and proton-induced single event upsets (SEU), single event latchup (SEL), single event transient (SET), and proton damage (ionizing and non-ionizing).


The work presented is sponsored by NASA Electronic Parts and Packaging (NEPP) Program's Electronics Radiation Characterization (ERC) Project, Defense Threat Reduction Agency (DTRA) under IACRO 01-4050/0001278, and NASA Flight Projects.



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## II. TEST TECHNIQUES AND SETUP

### *A. Test Facilities*

All SEE and proton-induced damage tests were performed between February 2000 and February 2001. Heavy Ion experiments were conducted at the Brookhaven National Laboratories (BNL) Single Event Upset Test Facility (SEUTF) and at Texas A&M University Cyclotron (TAMU). The SEUTF uses a twin Tandem Van De Graaf accelerator while the TAMU facility uses an 88" Cyclotron. Both facilities are suitable for providing various ions and energies for testing. At both facilities, test boards containing the device under test (DUT) were mounted in the test area. For heavy ions, the DUT was irradiated with ions with linear energy transfers (LETs) ranging from 0.59 to 120 MeV•cm$^2$/mg, with fluences from $1x10^5$ to $1x10^7$ particles/cm$^2$. Fluxes ranged from $1x10^2$ to $1x10^5$ particles/cm$^2$ per second, depending on the device sensitivity. Representative ions used are listed in Table I. LETs between the values listed were obtained by changing the angle of incidence of the ion beam on the DUT, thus changing the path length of the ion through the DUT. Energies and LETs available varied slightly from one test date to another.

Proton SEE and damage tests were performed at three facilities: the University of California Davis (UCD) Crocker Nuclear Laboratory (CNL), Tri-University Meson Facility (TRIUMF), and the Indiana University Cyclotron Facility (IUCF). Proton test energies incident on the DUT are listed in Table II. Typically, the DUT was irradiated to a fluence from $1x10^{10}$ to $1x10^{11}$ particles/cm$^2$, with fluxes on the order of $1x10^8$ particles/cm$^2$ per second.

The pulsed laser facility at the Naval Research Laboratory was used to generate single event transients in integrated circuits. The laser light used had a wavelength of 590 nm that resulted in a skin depth (depth at which the light intensity decreased to 1/e - or about 37% - of its intensity at the surface) of 2 microns.

Table I: Heavy Ion Test Facilities

| Facility |
|---|
| Brookhaven National Laboratories (BNL) Single Event Upset Test Facility (SEUTF) |
| Texas A&M University Cyclotron (TAMU) |

TABLE II: TEST HEAVY IONS

| | Ion | Energy, MeV | LET in Si, MeV•cm$^2$/mg | Range in Si, µm |
|---|---|---|---|---|
| BNL | $C^{12}$ | 102 | 1.42 | 193 |
| | $O^{16}$ | 131 | 2.53 | 145 |
| | $F^{19}$ | 145 | 3.31 | 126 |
| | $Si^{28}$ | 203 | 7.55 | 85.3 |
| | $Cl^{35}$ | 224 | 11.1 | 68.5 |
| | $Ti^{48}$ | 253 | 18.1 | 53.2 |
| | $Ni^{58}$ | 280 | 26.3 | 44.3 |
| | $Ge^{72}$ | 290 | 32.7 | 40.0 |
| | $Br^{79}$ | 305 | 36.9 | 38.7 |
| | $I^{127}$ | 370 | 60.1 | 34.3 |
| TAMU | $Ne^{20}$ | 298 | 2.5 | 331.0 |
| | $Ar^{40}$ | 599 | 7.4 | 243.7 |
| | $Kr^{84}$ | 1260 | 25.1 | 154 |
| | $Xe^{29}$ | 1935 | 47.1 | 127 |
| | $Au^{197}$ | 390 | 84.1 | 30.2 |
| | * $O^{16}$ | 880 | 0.59 | 3607 |
| | * $Ar^{40}$ | 1980 | 3.0 | 1665 |
| | * 55 MeV per nucleon tune | | | |

Table III: Proton Test Facilities and Particles

| Facility | Particle | Particle Energy, (MeV) |
|---|---|---|
| University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) | Proton | 26.6-63 |
| Tri-University Meson Facility (TRIUMF) | Proton | 50-500 |
| Indiana University Cyclotron Facility (IUCF) | Proton | 54-197 |

Table IV: Other Test Facilities

| |
|---|
| Naval Research Laboratory (NRL) Pulsed Laser SEE Test Facility<br>Laser: 590 nm, 3 ps pulse width, beam spot size ~1.5 µm |
| Goddard Space Flight Center Radiation Effects Facility (GSFC REF) |

### *B. Test Method*

Unless otherwise noted, all tests were performed at room temperature and with nominal power supply voltages.

#### *1) SEE Testing - Heavy Ion*

Depending on the DUT and the test objectives, one or more of three SEE test methods were used:

*Dynamic* – the DUT was exercised continually while being exposed to the beam. The errors were counted, generally by comparing DUT output to an unirradiated reference device or other expected output. In some cases, the effects of clock speed or device modes were investigated. Results of such tests should be applied with caution because device modes and clock speed can affect SEE results.

*Static* – the DUT was loaded prior to irradiation; data were retrieved and errors were counted after irradiation.

*Biased (SEL only)* – the DUT was biased and clocked while $I_{CC}$ (power consumption) was monitored for SEL or other destructive effects. In some SEL tests, functionality was also monitored.

In SEE experiments, DUTs were monitored for soft errors, such as SEUs and for hard errors, such as SEL. Detailed descriptions of the types of errors observed are noted in the individual test results.

SET testing was performed using a high-speed oscilloscope. Individual criteria for SETs are specific to the device being tested. Please see the individual test reports for details. [1]

Heavy ion SEE sensitivity experiments include measurement of the saturation cross sections and the Linear Energy Transfer ($LET_{th}$) threshold (the minimum LET value necessary to cause an effect at a fluence of $1x10^7$ particles/cm$^2$).

#### *2) SEE Testing - Proton*

Proton SEE tests were performed in a manner similar to heavy ion exposures in many regards. Differences include measuring the SEE cross section as a function of proton energy as opposed to LET, as well as differences in cumulative fluence and particle flux rates.

#### *3) Proton Damage Testing*

Proton damage tests were performed on biased devices with functionality and parametrics being measured either continually during irradiation or after step irradiations (for example, every 10 krad (Si), or every $1x10^{10}$ protons).

A proton test "lessons learned" document is currently under development. [2] Optocoupler characterization approaches used in this study are found in [1]

#### *4) Pulsed Laser Facility Testing*

The laser light used had a wavelength of 590 nm that resulted in a skin depth (depth at which the light intensity decreased to 1/e - or about 37% - of its surface intensity) of 2 microns. A pulse rate of 100 Hz was chosen. The DUT was mounted on an X-Y stage in front of a 100x lens that produced a spot size of about 1.5 microns. The X-Y stage could be moved in steps of 0.1 micron for accurate positioning of SEU sensitive regions in front of the focused beam. An illuminator together with a CCD camera and monitor were used to image the area of interest, thereby facilitating accurate positioning of the device in the beam. The pulse energy was varied with a neutral density filter and the energy was monitored by splitting off a portion of the beam and directing it at a calibrated energy meter.

#### *5) TID Testing*

TID testing was performed using a Co-60 source at the Goddard Space Flight Center Radiation Effects Facility (GSFC REF). The source is capable of delivering a dose rate of 0.5 Rad(Si)/s, with dosimetry being performed by an ion chamber probe.

## III. Test Results Overview

Abbreviations and conventions are listed in Table III. Abbreviations for principal investigators (PIs) are listed in Table IV. SEE test results are summarized in Table V. Unless otherwise noted, all $LET_{th}$s are in (MeV•cm$^2$/mg) and all cross sections are in cm$^2$/device. This paper is a summary of results. Complete test reports are available online at http://radhome.gsfc.nasa.gov [1].

Table V: Abbreviations and Conventions:

H = heavy ion test
P = proton test (SEE)
LET = linear energy transfer (MeV•cm$^2$/mg)
$LET_{th}$ = linear energy transfer threshold (the minimum LET value for which a given effect is observed for a fluence of 1x10$^7$ particles/cm$^2$ – in MeV•cm$^2$/mg)
$LET_{max}$ = highest tested LET
$LET_{eff}$ = effective LET
SEU = single event upset
SEL = single event latchup
SET = single event transient
SEFI = single event functional interrupt
DD = displacement damage
< = SEE observed at lowest tested LET
> = No SEE observed at highest tested LET
TID = total ionizing dose
σ = cross section (cm$^2$/device, unless specified as cm$^2$/bit)
$\sigma_{SAT}$ = saturation cross section at $LET_{max}$ (cm$^2$/device, unless specified as cm$^2$/bit)
LDC = lot date code
CTR = current transfer ratio
DAC = digital to analog converter
ADC = analog to digital converter
LED = light emitting diode
DRAM = dynamic random access memory
SRAM = static random access memory
MOSFET = metal oxide semiconductor field effect transistor
PAL = Programmable array logic device
ALU = Arithmetic Logic Unit
$V_S$ = Supply voltage
$I_F$ = Forward current
$V_F$ = Forward voltage
$V_{IN}$ = Input voltage
N/A = Not applicable
p-p = peak-to-peak
Cat = category

Table VI: List of Principal Investigators

| Principal Investigator (PI) | Abbreviation |
|---|---|
| Kenneth LaBel | KL |
| Robert Reed | RR |
| Jim Howard | JH |
| Ray Ladbury | RL |
| Scott Kniffin | SK |
| Tony Sanders | TS |

Table VII: List of Categories

| Category | Implications |
|---|---|
| 1 | Relatively hard or immune to SEEs; recommended for spaceflight |
| 2 | Somewhat susceptible to SEEs; may need some error detection and correction (EDAC) when used in an application |
| 3 | Fairly soft devices that are very susceptible to SEEs; use with great caution. Intensive EDAC may be necessary |
| 4 | Not recommended for spaceflight. Destructive conditions, such as latchup, total dose failure, or burnout were observed in these devices at low levels. |

TABLE VII: SUMMARY OF SEE TEST RESULTS

| Part Number | Function | LDC | Manufacturer | Particle: (Facility)P.I. | Testing Preformed | Summary of Results | Cat |
|---|---|---|---|---|---|---|---|
| **ADCs:** | | | | | | | |
| AD1674 | ADC | 9848 | Analog Devices | H: (BNL) JH/RR | SEU; SEL | SEL $LET_{th}$ >37, $s_{sat}<1x10^{-7}$. For positive input: SEU LETth<2.6 $s_{sat}<1.6x10^{-3}$. For negative input: SEU $LET_{th}$=5.2 $s_{sat}=2.2x10^{-4}$ | 2 |
| AD6640 | ADC | 9951 | Analog Devices | H:(BNL) JH/RL/RR | SEU; SEL | SEUs $LET_{th}$ < 1; s ~ 1-2x$10^{-3}$;<br>s ~ 1-2x$10^{-4}cm^2$ per bit;<br>SEFIs observed; 26.2 < $LET_{th}$ <37; s ~ 1x$10^{-5}$;<br>No SELs observed; SEL $LET_{th}$ >37 | 2 |
| SPT7760 | ADC 1 GSPS | N/A | Signal Processing Tech. | H:(TAMU)RR | SEU; SEFI Functional Failure | Functional failure occurred at LET=84, power cycle was required to recover. s=2x$10^{-2}$ for functional failure. No functional failure at LET=50 to a fluence of 1x$10^{7}$ p/$cm^2$ $LET_{th}$<1.8, $s_{sat}$~2x$10^{-3}cm^2$/device | 2 |
| **DC-DC Converters:** | | | | | | | |
| AFL12005SX/CH | DC-DC | 0006 | Lambda | H: (BNL) JH/RR | SET | For Cl(LET=11.4) No transients observed. Saw destructive failure under low-voltage, high-load conditions during irradiation of sector 2. Sectors 1,3,4 not tested. | 3 |
| AFL12012DX/CH | DC-DC | 0005 | Lambda | H: (BNL) JH/RR | SET | For Br(LET=37) No transients or destructive events observed for high voltage low load. Saw destructive failure under low-voltage, high-load conditions during irradiation of sector 1. | 3 |
| AFL12015DX/CH | DC-DC | 0005 | Lambda | H: (BNL) JH/RR | SET | For Br(LET=37) No transients observed. No failure in sectors 1,3,4. Failure at low-voltage high-load in sector 2 led to a destructive event. | 3 |
| DVHF2803R3SF | DC/DC | 9910 | Virginia Power Technology | H:(BNL) JH | SET/DD | For Br(LET=37) No Destructive events observed. Destructive event at LET=60 and full loading. Small SETs observed at low rate. | 2 |
| LCM-120 | DC-DC | 0003<br>9952 | Interpoint | H:(BNL) JH/RR<br>Laser:(NRL) JH<br>TID:<br>(GSFC-REF)TS | SET; SEL; TID | HI: SET LETth <2.6, $s_{sat}$ ~$10^{-3}$<br>SETs 50-100 µs in duratiion<br>P: No SETs observed to s <3x$10^{-12}$<br>P: (UCD) TID failure observed at proton doses of ~ 20 and 25 krads (Si) | 2 |
| MDI3051RES05ZF | DC-DC | 0013 | Modular Devices Inc. | H:(BNL) JH/RR | SET | For Cl(LET=11.4) No transients observed. Sector 2: failure at low-voltage high-load led to a destructive event. | 3 |
| MDI3051RES12ZF | DC-DC | 0013 | Modular Devices Inc. | H:(BNL) JH/RR | SET | For Cl(LET=11.4) No transients or failures. For Ni(LET=28) no SETs in Sector 2: failure at 120 V high-load led to a destructive event. | 3 |
| MDI3051RES15ZF | DC-DC | 0013 | Modular Devices Inc. | H:(BNL) JH/RR | SET | For Cl(LET=11.4) No transients or failures. For Ni(LET=28) no SETs observed. Sector 2: failure at 120 V moderate-load led to a destructive event. | 3 |

TABLE VII (CONT.): SUMMARY OF SEE TEST RESULTS

| Part Number | Function | LDC | Manufacturer | Particle: (Facility)P.I. | Testing Preformed | Summary of Results | Cat |
|---|---|---|---|---|---|---|---|
| **Linear Bipolar:** | | | | | | | |
| LM-124 | Op Amp | N/A | National Semiconductor | Laser:(NRL) JH | SET | Several SETs observed, see poster [3] for application specific test results | 2 |
| LM-139 | Comparator | N/A | National Semiconductor | H: (BNL) JH | SET | Transients observed; depended on input differential voltage, see poster [3] | 2 |
| HS-139 | Comparator | N/A | Harris/Intersil | H:(BNL) JH | SET | Transients observed; depended on input differential voltage, see poster [3] | 2 |
| LM-148 | Op Amp | 9905 | Fairchild | P:(UCD) SK/RR | SET;SEU | HI: No SEL to I(LET=60); SET $LET_{th}$<2.6, $s_{sat}=2x10^{-5}$; Various pulse height and width<br>P: No SETs observed, no SEUs observed; no performance degradation to $7.44x10^{11}$ protons/$cm^2$ | 2 |
| **Board Tests:** | | | | | | | |
| Pentium III | Processor | N/A | Intel | P:(IU) JH<br>H: (TAMU) JH | SEE; TID; | SEL: No SELs observed to LET>20; No SELs observed for 200 MeV proton; SEU: non-destructive errors were observed, P: SEFI: were observed. See poster [4] | 3 |
| AMD K7 | Processor | N/A | Advanced Micro Devices | P:(IU) JH<br>H: (TAMU) JH | SEU/SEL | No SELs observed; SEU: non-destructive errors were observed, P: SEFI: were observed. See poster [4] | 4 |
| **Miscellaneous:** | | | | | | | |
| IL710 | Isolator | 9950 | Non Volatile Electronics | H:(BNL) RR | SEL; SET | No SEL observed $LET_{th}$>60, SETs observed beginning near LET=11, $s_{sat}=2.5x10^{-5}$ | 2 |
| Mii42142 | Power Op Amp | N/A | Micropac | H:(BNL) SK/RR<br>P:(UCD) SK/RR | SET; SEGR | HI:$SET_{th}$<11.4 (dependent on bias) conditions;<br>$LET_{th}$ for $SEGR_{th}$<37 (application specific)<br>P: No SETs obseved | 4 |
| Mii53124 | Power MOSFET Optocoupler | N/A | Micropac | H:(BNL) SK/RR | SET; SEGR | No SET;<br>$LET_{th}$ for SEGR = 37 | 3 |
| Mii53250 | Relay | N/A | Micropac | H:(BNL) SK/RR | SET; SEGR | No SET;<br>$LET_{th}$ for SEGR >60 | 3 |
| Mii53253 | Power MOSFET Optocoupler | N/A | Micropac | H:(BNL) SK/RR | SEGR | No SET;<br>$LET_{th}$ for SEGR = 60 | 3 |
| Mii53258 | Relay | N/A | Micropac | H:(BNL) SK/RR | SET; SEGR | No SET;<br>$LET_{th}$ for SEGR = 60 | 3 |
| 6651 | Optocoupler | 0027 | Agilent (Hewlett Packard) | P:(UCD) SK | SET | SETs observed with angular dependence | 3 |

TABLE VIII: SUMMARY OF DISPLACEMENT DAMAGE (DD) TEST RESULTS

| Part Number | Function | LDC | Manufacturer | Particle: (Facility)P.I. | Testing Preformed | Summary of Results |
|---|---|---|---|---|---|---|
| **Displacement Damage Test Results:** | | | | | | |
| OD800 | LED | N/A | Optodiode | P:(UCD) SK/RR | DD | Output power noted 20% degradation at $6.6x10^{10}$ p/cm$^2$ |
| P2824 | Optocoupler | N/A | Hamamatsu | P:(UCD) SK | DD | CTR degradation observed at $1x10^{10}$ p/cm$^2$ (flight lot) |
| 66099 | Optocoupler | 0048 | Micropac | P:(UCD) SK | DD | CTR degradation observed at $2.5x10^{11}$ p/cm$^2$ (non flight lot) |
| 4N49 | Optocoupler | 9803<br>9818 | Micropac | P:(UCD) SK | DD | No $V_{CE}$ degradation to $5x10^{10}$ p/cm$^2$. Some $V_{CE}$ degradation was observed for some conditions at $1x10^{11}$ p/cm$^2$ |
| 4N49 | Optocoupler | 0048 | Micropac | P:(UCD) SK | DD | CTR degradation observed at $3x10^{10}$ p/cm$^2$ (non flight lot) |
| 4N49S | Optocoupler | 9736 | Micropac | P:(UCD) SK | DD | Some CTR degradation observed at $1x10^{12}$ p/cm$^2$ (flight lot) |
| 6N134 | Optocoupler | 0046 | Micropac | P:(UCD) SK | DD | CTR degradation observed at $1x10^{12}$ p/cm$^2$ (non flight lot) |
| 6N140 | Optocoupler | 0048<br>9724 | Micropac | P:(UCD) SK | DD | CTR degradation observed at $7.5x10^{11}$ p/cm$^2$ (flight lot); and at >$1x10^{12}$ (non flight lot) |
| Mii42142 | Power Op Amp | N/A | Micropac | P:(UCD) SK/RR | DD | No SET/SEGR to $7.44x10^{12}$ p/cm$^2$; 18% drop in output current after $7.44x10^{12}$ p/cm$^2$ |
| Mii53124 | Power MOSFET Optocoupler | N/A | Micropac | P:(UCD) SK/RR | DD | No SET, no significant degradation to $1x10^{12}$ p/cm$^2$ |
| Mii53250 | Relay | N/A | Micropac | P:(UCD) SK/RR | DD | No SET, no significant degradation to $1x10^{12}$ p/cm$^2$ |
| Mii53253 | Power MOSFET Optocoupler | N/A | Micropac | P:(UCD) SK/RR | DD | No SET, no significant degradation to $1x10^{12}$ p/cm$^2$ |
| Mii53258 | Relay | N/A | Micropac | P:(UCD) SK/RR | DD | No SET, no significant degradation to $1x10^{12}$ p/cm$^2$ |

TABLE IX: SUMMARY OF SEL TEST RESULTS

| Part Number | Function | LDC | Manufacturer | Particle: (Facility)P.I. | Testing Preformed | Summary of Results** | * Cat |
|---|---|---|---|---|---|---|---|
| **Linear Bipolar Devices:** | | | | | | | |
| CMP402 | Comparator | 0010 | Analog Devices | H:(BNL) RL/RR | SEL | No SEL observed up to $LET_{eff}$=119.8 | 1 |
| OP16 | Op Amp | 9917 | Analog Devices | H:(BNL) JH/RL | SEL | No SEL observed up to $LET_{eff}$=37.3 | 1 |
| OP37 | Op Amp | 9925 | Analog Devices | H:(BNL) JH/RL | SEL | No SEL observed up to $LET_{eff}$=59.9 | 1 |
| OP42 | Op Amp | 9750 | Analog Devices | H:(BNL) JH/RL | SEL | No SEL observed up to $LET_{eff}$=37.3 | 1 |
| **ADC/DAC:** | | | | | | | |
| AD7535 | DAC | 9804 | Analog Devices | H:(BNL) JH/RR | SEL | No SEL to $LET_{eff}$=74.6 | 1 |
| AD7564 | DAC | 9950 | Analog Devices | H:(BNL) RL/RR | SEL | No SEL to $LET_{eff}$=59.9 | 1 |
| AD7664 | ADC | 864065-2 | Analog Devices | H:(BNL) JH | SEL | SEL $LET_{th}$ ~ 8-10, s = $2\text{-}3\text{x}10^{-4}$ | 3 |
| AD7854 | ADC | 9930 | Analog Devices | H:(BNL) RL/RR | SEL | SEL 6.7<$LET_{th}$<11.4, $s_{sat}$ <$1\text{x}10^{-3}$. | 4 |
| AD7858 | ADC | 0026 | Analog Devices | H:(BNL) RL/RR | SEL | SEL $LET_{th}$ 11.4-22.8, $s_{sat}$ <$1\text{x}10^{-3}$. | 4 |
| AD7888 | ADC | 0002, 0016 | Analog Devices | H:(BNL) RL/RR | SEL | SEL $LET_{th}$ 16.7-22.8, $s_{sat}$ <$1.3\text{x}10^{-5}$. | 4 |
| **Miscellaneous:** | | | | | | | |
| ADG704 | Multiplexer | 0008 | Analog Devices | H:(BNL) RL/RR | SEL | SEL $LET_{th}$~16, $s_{sat}$<$1.1\text{x}10^{-4}$. | 4 |
| AMP01 | Inst. Amp | 9922 | Analog Devices | H:(BNL) RL/KL/JH | SEL | Hard Failure $LET_{th}$>32.7; failure more likely at normal incidence Susceptible to SET [5] | 3 |
| INA117 | Diff. Amp | N/A | TI/Burr-Brown | H:(BNL) RL | SEL | No SEL observed up to $LET_{eff}$=119.8 | 1 |
| MAX313 | Switch | 9823 | Maxim | H:(BNL) JH/RR | SEL | No SEL observed up to $LET_{eff}$=59.9 | 1 |
| MAX4503 | CMOS switch | N/A | Maxim | H:(BNL) JH | SEL | No SEL observed up to $LET_{eff}$=119.8 | 2 |
| MAX4528 | CMOS analog switches | 9816 | Maxim | H:(BNL) RL/RR | SEL | No SEL observed up to $LET_{eff}$=59.9 | 1 |
| MAX4583 | CMOS analog switches | 0007 | Maxim | H:(BNL) RL/RR | SEL | No SEL observed up to $LET_{eff}$=59.9 | 1 |
| MAX4617 | MUX | N/A | Maxim | H:(BNL) RL | SEL | No SEL observed up to $LET_{eff}$=119.8 | 1 |
| MAX584 | Vref | 9838 | Maxim | H:(BNL) RR | SEL | No SEL observed up to $LET_{eff}$ = 37.3 | 1 |

Note: * Rating applies only for SEL not for other SEE concerns.
** All parts tested to a minimum fluence of 1.0 x $10^7$ particles/$cm^2$

## IV. SEE TEST RESULTS AND DISCUSSION

### *A. ADCs:*

#### *1) AD1674*

The Analog Devices AD1674 analog-to-digital converter (ADC) was tested for SEU and SEL at BNL using ions with effective LETs ranging from 2.6 MeV·cm2/mg (Oxygen) to approximately 56 MeV•$cm^2$/mg (Bromine at 45 degrees). No SEL events were observed for normal incidence Br up to a fluence of $1\text{x}10^7$ ions/$cm^2$, or for a fluence of $8\text{x}10^5$ ions/$cm^2$ Br ions incident at 45 degrees. To investigate SEUs in the AD1674, the output of the device under test (DUT) was compared to that of a reference chip located outside the beam and given an identical input to that of the DUT. Device upset cross section vs. LET was measured for both positive and negative inputs to the ADCs. For all tests, the lowest two significant bits were masked off to avoid counting noise as upsets.

For positive device input, the threshold LET was about 2-3, and the limiting cross section was approximately $1.6\text{x}10^{-3}cm^2$.

For negative input, the threshold LET for upset was found to be about 5-8, with a limiting cross section of about $2.2 \times 10^{-4} cm^2$, about an order of magnitude lower than for positive input. This indicates that the mechanisms underlying upsets under conditions of positive input and negative input are probably distinct. For additional information refer to the GSFC radiation group website. [1]

The hardware setup for this testing is shown via a block diagram pictured in Figure 1. The data taken for the case of 2 masked bits is featured in Figure 2. [6]

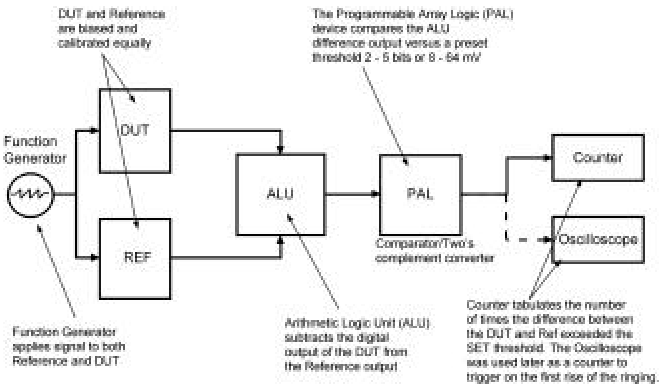


Figure 1. Block diagram of the experimental setup for testing the AD1674 ADC.

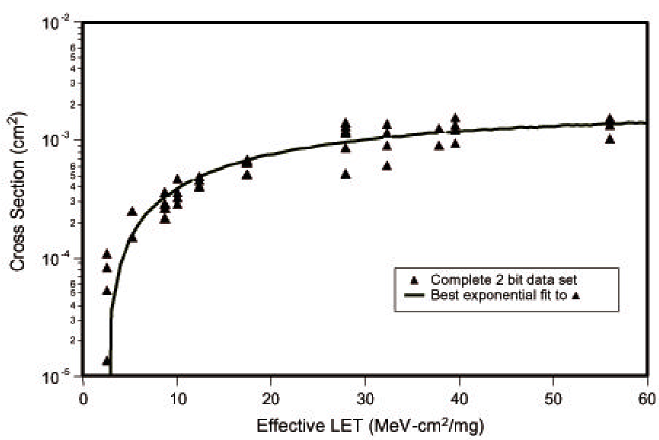


Figure 2. Cross section versus effective LET curve for the AD1674.

*2) AD6640*

The Analog Devices AD6640 12-bit ADC was tested for SEU, SEL, and single event functional interrupt (SEFI). The AD6640 is a 65 MHz, 12-bit ADC fabricated in Analog Devices XFCB dielectrically isolated bipolar process. Because of the high speed required in this test (15-40 MHz), noise was a concern, and several steps were taken to ensure that noise was kept to a minimum. Even so, several least significant bits had to be masked off to avoid triggering on noise. The number of masked bits varied from 3 at the lowest frequencies up to 5 at the higher frequencies. SEUs were observed even for carbon ions, which have LET=1.44 MeV•$cm^2$/mg, indicating that the LET threshold is less than 1 MeV•$cm^2$/mg. The limiting cross section for SEU was observed to be about 1-$2 \times 10^{-3} cm^2$ per device. When the cross sections were calculated per bit, based on the number of bits available to cause upsets (that is 12 - the number of masked bits), these per bit cross sections gave a fairly tight distribution with limiting value on the order of 1-$2 \times 10^{-4} cm^2$ per bit.

Single event functional interrupts were also observed. These events caused every conversion to be in error after they occurred until they were reset by cycling power to the device. The threshold LET for these SEFIs was between 26.2 and 37 MeV•$cm^2$/mg and the limiting cross section was on the order of $1 \times 10^{-5} cm^2$ per device. No evidence of SEL was observed up to a fluence of $2 \times 10^6$ ions/$cm^2$ for $Br^{79}$. [7]

*3) SPT7760*

The SPT7760 is an Emitter Coupled Logic (ECL) based 1 giga-sample per second (1 Gsps) 8 bit + overflow flash ADC manufactured by Signal Processing Technologies, Incorporated. It has an input range of 0 to 2 V and is fully parallel with 8 bits of resolution (256 values) plus an additional over-range bit. The analog input has a bandwidth of over 900 MHz and a capacitance of < 15 pF.

The output byte-stream is at differential ECL levels. It is de-multiplexed into two identical ports (labeled ports A and B) each with 9 bits (8 + overflow) plus clock at a maximum output rate of 500 Msps. The aggregate throughput is therefore 1 Gsps. The device is supplied in an 80 pin MQUAD package with the option of MIL-STD-883 screening.

The SPT7760 was tested for susceptibility to heavy ion induced SEUs at TAMU using beams of Ne, Kr and Xe ions. Because the input was a constant dc voltage, the output from the ADC was also constant unless an SEU occurred. As a result, SEUs were identified by comparing each conversion to the previous conversion. Any changes were recorded as SEUs and the data were stored on a PC for post-processing. [8].

Figure 3 shows results from heavy ion SEU tests at TAMU. The plot shows measured cross sections for the device for various dc input conditions (-2 to 0 volts), frequencies (10, 100 and 1000 MHz) and LETs (1.28, 20 and 50). No clear dependence of cross section on input voltage or frequency is evident in the data.

Functional failure occurred at LET=84 and a power cycle was required to recover. The cross section for functional failure was approximately $2 \times 10^{-2} cm^2$. No functional failures were observed up to LET=50 for a fluence of $1 \times 10^7$ p/$cm^2$. The threshold LET for SEU was less than 1.8 and the limiting cross section was on the order of about $2 \times 10^{-3} cm^2$.

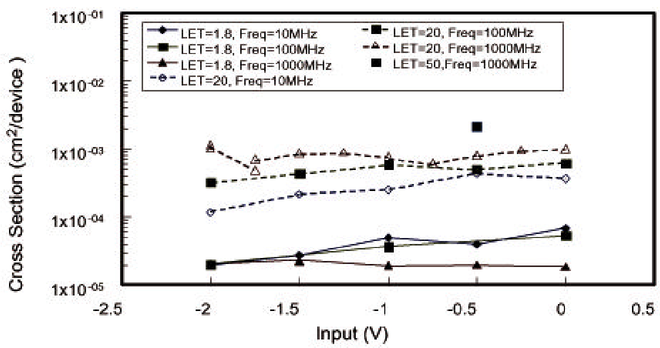


Figure 3. Heavy Ion induced SEU testing on the SPT7760.

### B. DC-DC Converters:

#### 1) AFL12005SX/CH

The AFL12005SX/CH Advanced Analog Lambda, Inc. DC/DC Converter was tested for susceptibilty to destructive single event effects and single event transients at BNL using $Cl^{35}$ ions with an LET of 12.

The DC/DC converter was tested under bias conditions of 126 V with a load of approximately 7.7 W and 113 V with a load of approximately 56.4 W. The DC/DC converter was de-lidded and the active device area divided into four circular regions. With the active section of the converter in the left half of the device, the four regions, numbered 1 through 4. Region #2 contained the power MOSFETs.

For the first of the conditions (high voltage and low loading), no single event transients were observed at the output voltage port and no destructive events were observed for any of the four regions. However, the device experienced a destructive event when region #2 was exposed under the second set of conditions. That event resulted in the output dropping to zero volts and a loss of functionality that was not recovered after a power cycle. No transient events were observed, as the device's first event was destructive. This indicates that the device is susceptible to destructive errors with a threshold LET less than or equal to 12 with a cross section that cannot be determined from the current study. [9]

#### 2) AFL12012DX/CH

The AFL12012DX/CH Advanced Analog Lambda, Inc. DC/DC Converter was tested for single event destructive and transient susceptibility at BNL using $Br^{79}$ ions with an LET of 37.

The DC/DC converters were tested under bias conditions of 120 and 126 V with a load of approximately 7.7 W and 116 V with a load of approximately 57.6 W. The DC/DC converter was de-lidded and the active device area divided into four circular regions. With the active section of the converter in the left half of the device, the four regions, numbered 1 through 4, start in the upper left hand corner and proceed clockwise. The power MOSFETs were primarily located in region #2, but may have overlapped into region #1. For the first of the conditions (high voltage and low load), no single event transients were observed at the output voltage port and no destructive events were observed for any of the four regions. However, the device did experience a destructive event when region #1 was exposed under the second set of conditions. That event resulted in the output dropping to zero volts and functionality being lost. Cycling power did not return the device to functionality. This indicates that this device is susceptible to destructive failure with a threshold LET less than 37 and a cross section that cannot be determined from this study. The susceptibility of the AFL12005SX/CH) to destructive failure with threshold LET less than 12 may indicate that the threshold LET is substantially lower than 37. [10]

#### 3) AFL12015DX/CH

The AFL12015DX /CH Advanced Analog Lambda, Inc. DC/DC Converter was tested for single event destructive and transient susceptibility at BNL using ions with an LET of 37 ($Br^{79}$).

The DC/DC converters were tested under bias conditions of 126 V with a load of approximately 7.8 W and 116, 117, and 113 V with a load of approximately 55.6 to 58.5 W. The DC/DC converter was de-lidded and the active device area divided into four circular regions. With the active section of the converter in the left half of the device, the four regions, numbered 1 through 4, start in the upper left hand corner and proceed clockwise. Region #2 contained the power MOSFETs.

For the first of the conditions (high voltage and low load), no single event transients were observed at the output voltage port and no destructive events were observed for any of the four regions. However, the device did experience a destructive event when region #2 was exposed under bias conditions of 116, 117, and 113 V at a loading of approximately 55.6 to 58.5 W. That event resulted in a loss of device functionality and a drop of the device output to zero volts. Functionality could not be restored by cycling power. No transient events were observed, as the device's first event was destructive. This result indicates that the device is susceptible to a destructive failure with a threshold LET less than or equal to 37, and with a cross section that cannot be determined from the current study. The fact that another AFL part (AFL12005SX/CH) exhibited a similar destructive failure at an LET of 12 suggests that the threshold LET could be considerably lower than 37. [11]

#### 4) DVHF2803R3SF

The DVHF2803R3SF/HBM DC/DC Converters from Virginia Power Technology, Inc. were tested to determine their susceptibility to destructive single event effects and single event transients at BNL using ions with LETs of 37 ($Br^{79}$) and 59.8 ($I^{127}$).

The DC/DC converters were tested under bias conditions of 28 and 35 V with loads of approximately 1.65 and 9.9 W. The DC/DC converter was de-lidded and the active device area was divided into three circular regions. Region 1 contains the power devices and is located near the upper right-hand corner, region 2 is the upper left-hand side and region 3 the lower left-hand side. The lower right contained only passive devices.

For these converters both destructive events and transients were observed, albeit at high LET values. Because the destructive events may be of greater concern, they will be discussed first. DUTs 1 and 2 were test with Bromine ions (LET = 37) at low and high load conditions and with both nominal (28 V) and high (35 V) input conditions. Under all of these conditions, no destructive events were observed. For runs with Iodine ions (LET = 59.8), destructive events were observed. However, these events occurred only when the device was operated at full load. Both DUTs passed at Iodine under low load conditions. Additionally, DUT 2 passed one run with input voltage 28 V and high load with Iodine, but failed on the next run when the input voltage was raised to 35 V. The location of the power devices and the structures surrounding them made it impossible to irradiate the parts at angles other than normal incidence, so effective LETs between the nominal ion LETs could not obtained. Therefore, the threshold LET for destructive events is between 37 and 59.8. For the two destructive events observed, the average cross section for the event is approximately 2 x $10^{-6}$cm$^2$, although the low statistics and uncertainties in the final fluence dictate large error bars for this number.

Transient errors were also observed as positive pulses of magnitude up to 500 mV superimposed on the output voltage. Transient durations were on the order of a microsecond, although the exact duration could not be determined because of limitations on the timescales of the digitizing scope. Transients were observed on both devices (although DUT 2 was approximately an order of magnitude more sensitive) at both LET = 37 and 59.8 MeV•cm$^2$/mg. This indicates that the threshold LET for these events is less than 37. No lower bound can be determined from the current data. However, cross sections were small ($10^{-7}$ to $10^{-5}$ cm$^2$), suggesting a fairly low event rate even for low LET thresholds. Moreover, the short duration of the transients suggests that they could be substantially mitigated by filtering. These considerations lowered the priority of exact determination of the LET threshold for these transients. [12]

*5) LCM-120*

SET and SEL testing were performed on the Interpoint LCM-120 line conditioning module. This device was tested at three facilities, BNL, Naval Research Laboratory Plused Laser SEE test facility, and University of California Crocker Nuclear Laboratory.

Based on these test runs, it has been determined that the LCM-120 is susceptible to single event transients on the output of the device when exposed to heavy ions. The threshold for the transients is <2.6 (lowest LET used) and the saturation cross section is approximately $10^{-3}$ cm$^2$. The transients all lasted on the order of 50-100 µs. The transients took the form of voltage drops from the nominal output voltage of 24 V, and they ranged from a volt to approximately 18 V. The large voltage transients exhibited very rapid fall times, and because of limitations of the digital scope to capture such rapid events, it cannot be ruled out that the drop was all the way to ground.

Despite the very low threshold LET observed for heavy ions, proton testing at UCD did not reveal any proton induced SET sensitivity to a cross section of less than 3 x $10^{-12}$ cm$^2$. The sensitivity to proton-induced SETs at lower cross sections could not be evaluated due to the total dose restrictions of the LCM-120. Total dose failure was observed at the UCD facility at proton doses of approximately 20 and 25 krads (Si) for the two devices tested there [13]. TID testing was performed on the LCM-120, at the GSFC-REF using Co-60 ? rays. The device exceeded specifications between 23-28 krads (Si) [14].

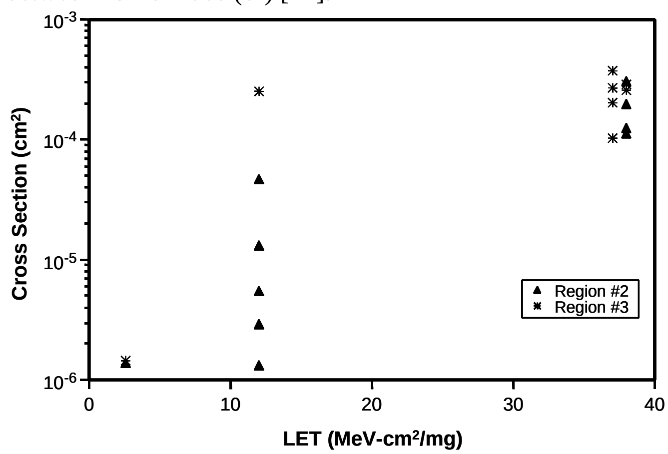


Figure 4. Plot of LCM-120 SET cross section as a function of the ion LET. Data for two Device s Under Test (DUT) are shown.

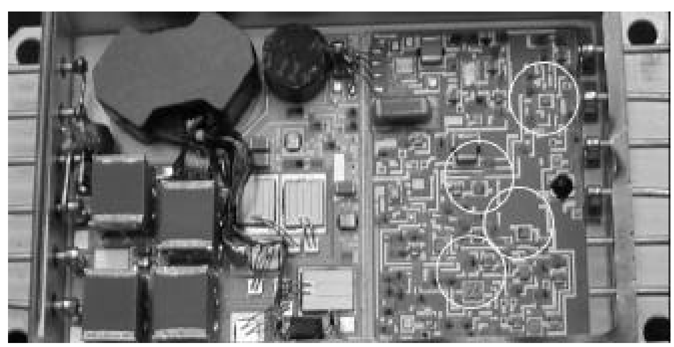

Figure 5. Photograph of the LCM-120 device with the four sensitive components circled in yellow.

*6) MDI3051RES05ZF*

The MDI3051RES05ZF DC/DC Converter from Modular Devices, Inc. was tested for susceptibility to single event induced transients and destructive events induced at the BNL.

The DC/DC converter was tested under bias conditions of 126 V with a load of approximately 7 W, and 113 V with a load of approximately 52.9 W. The DC/DC converter was de-lidded and the active device area divided into two circular regions. With the active section of the converter in the upper left quadrant of the device, region 1 is in the upper left-hand corner and region two is to the immediate right of region 1. Region #2 contained the power MOSFETs.

For the first of the conditions (126 V and a load of 7 W), no single event transients were observed at the output voltage port and no destructive events were observed for either of the two regions. However, the device did experience a destructive event when region #2 was exposed under the second set of conditions (113 V, 52.9 W load). That event resulted in the output dropping to zero volts and the device losing functionality. Functionality could not be restored by cycling power. No transient events were observed, as the device's first event was destructive. This destructive condition occurred for the only LET ion used (LET = 12). These data indicate that the device is susceptible to a single event induced destructive mechanism with threshold LET less than 12 and a cross section that cannot be determined from the current study. [15]

*7) MDI3051RES12ZF*

The MDI3051RES12ZF DC/DC Converter from Modular Devices, Inc. was tested for susceptibility to single event induced transients destructive events at BNL.

The DC/DC converters were tested with an input voltage of 120 V and loads of approximately 7.8, 18.9, 37.1 and 55.5 W using a beam of Cl ions (LET=12). Testing was also done at 120 V and loads of approximately 8, 19.2, 37.6 and 56.3 W for a beam of Ni ions (LET=26.7). The DC/DC converter was de-lidded and the active device area divided into two circular regions. With the active section of the converter in the upper left quadrant of the device, region 1 was in the upper left-hand corner and region two was to the immediate right of region 1. Region 2 contained the power MOSFETs.

No single event transients were observed while irradiating region 2 with either ion for any test conditions. Previous testing had indicated that region 1 was not sensitive. No destructive events were observed for the high load conditions. However, the device did experience a destructive event when region #2 was exposed to Ni when the input was 120 V and the load was 56.3 W. That event resulted in the output dropping to zero volts and the device losing functionality. Functionality could not be restored by cycling power. No transient events were observed, as the device's first event was destructive. This indicates that the device is susceptible to a destructive condition with a threshold LET between 12 and 28. The cross section for this destructive mechanism cannot be determined from this study. [16]

*8) MDI3051RES15ZF*

The MDI3051RES15ZF DC/DC Converter from Modular Devices, Inc. was tested for susceptibility to single event induced transients and destructive events at BNL.

The DC/DC converters were tested under conditions of 120 V input and loads of approximately 8.2, 19.4, 38.3 and 56.6 W for the Chlorine beam (LET=12). Testing was also done for 120 V input and loads of approximately 8.2, and 38 W and 75 V input and 38.7 W for the Nickel beam. The DC/DC converter was de-lidded and the active device area divided into two circular regions. With the active section of the converter in the upper left quadrant of the device, regions 1 was in the upper left-hand corner and region two was to the immediate right of region 1. Region 2 contained the power MOSFETs.

No single event transients were observed at the output voltage port for any of the conditions tested under irradiation by either ion. No destructive events were observed for region #2 under conditions of high load. (Other testing had indicated that region #1 was not sensitive). However, the device did experience a destructive event with a Nickel beam incident on region #2 while the input voltage was 120 V and the load was 38 W. That event resulted in the output dropping to zero volts and the device losing functionality. Functionality could not be restored by cycling power. No transient events were observed, as the device's first event was destructive. These data indicate that this device is susceptible to a destructive mechanism with an LET threshold between 12 and 28. The cross section cannot be determined from this study. [17]

## *C. Linear Bipolar Devices:*

*1) LM124, LM139, and HS139*

The National Semiconductor LM124 Op Amp was tested for transient susceptibility at Naval Research Laboratory Plused Laser SEE test facility.

The National Semiconductor LM139, and the Harris/Intersil HS139 Comparators were tested for heavy ion induced transient susceptibility at BNL.

Transients were observed. For application specific test results see C. Poivey, et al., "Development of a Test Methodology for Single Event Transients (SETs) in Linear Devices" [3].

*2) LM148*

The Fairchild LM148 (LDC9905) quad op amp was irradiated with 63MeV protons at UCD. The device was biased with $V_S$ = 15V and $I_L$ = 2mA and a 10kHz, 10V peak-to-peak sine wave as an input. No SETs and no performance degradation were observed up to a fluence of $7.44 \times 10^{11}$p/cm$^2$.

The Fairchild LM148 (LDC9905) quad op amp was irradiated with heavy ions at BNL to determine the SET/SEL characteristics of the device. Test conditions were identical to those at UCD. An SET was defined as an output deviation of ±0.5V from the expected value of the output sine wave. The SET $LET_{th}$ = 3.7MeV•cm$^2$/mg and $\sigma_{sat}$ = $8 \times 10^{-4}$cm$^2$. No SELs were observed in testing. [18]

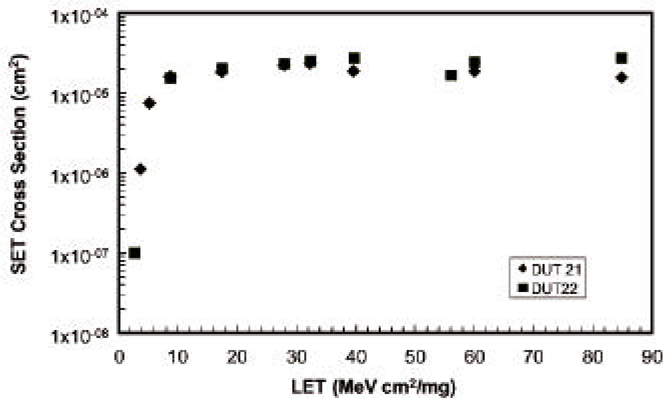

Figure 6. Heavy ion SET cross section data for two LM148 devices.

*D.Board Tests:*

*1) Pentium III*

Intel Pentium III processors were tested for SEE and TID at TAMU, and at the IUCF. No SELs observed for LETs up to at least 20. No SELs observed for 200 MeV protons. Non-destructive SEU errors were observed in various regions of the processors and SEFIs were observed (where the processor halted). See J.W. Howard et al., "Total Dose and Single Event Effects Testing of the Intel Pentium III (P3) and AMD K7 Microprocessors". [4] and [19]

*2) AMD K7*

AMD K7 processors were tested for SEU and SEL at TAMU and at the IUCF. No SELs were observed. Non-destructive SEU errors were observed in various regions of the processors and SEFIs were observed (where the processor halted). See J.W. Howard et al., "Total Dose and Single Event Effects Testing of the Intel Pentium III (P3) and AMD K7 Microprocessors". [4] and [19]

*E. Miscellaneous:*

*1) IL710*

The Non Volatile Electronics (NVE) IL710 digital isolator was tested at BNL to determine its sensitivity to heavy ion induced single event effects (SEE). Two samples were tested, one manufactured using 1.2 µm fabrication process and the other manufactured using a 0.6 µm process.

During testing we observed that the SETs were typically 5µs in duration. Using an iris to modulate the beam size, we were able to focus the beam on the entire DUT or on either the output or the input side of the DUT. The SET cross section obtained when exposing the input side of the DUT is between $6x10^{-7}$ and $1.2x10^{-6}$ for an LET = 37 MeV•cm$^2$/mg. No upsets were observed when exposing the output side to a fluence of $1x10^{7}$ ions/cm$^2$. This clearly indicates that the input side of the device is more sensitive to SETs. Neither IL710 type experienced SELs for LETs up to 37. [20]

*2) Mii42142*

The Micropac Mii42142 power op amp was irradiated with heavy ions at BNL to determine devices susceptibility to SET and other SEE. Irradiation took place under several bias conditions, including combinations of $V_S$ = 8V or 15V and $V_{-IN}$ = 0.1V, 0.6V, or 1.3V, $V_{+IN}$ was set to ground. The device was set to a Gain of 10 and inverted output with a 5Ω load. The SET trigger levels were based on $V_{-IN}$ and set at –1.25V, –7.0V and –15V respectively. The device was deemed to have experienced a SET if the device output deviated from the expected level by the amount set by the trigger levels and a single event induced destructive effect if the device failed to reset after power cycling. The heavy ion $SET_{TH}$ = 11.4 MeV•cm$^2$/mg. The heavy ion $\sigma_{sat}$ = $2x10^{-4}$cm$^2$ for transients at $V_{-IN}$ = 0.1V at both values of $V_S$ (Figures 7 and 8). An SEGR occurred at LET = 60 MeV•cm$^2$/mg with $V_S$ = 8V and $V_{-IN}$ = 0.1V. No proton SETs were observed. [21]

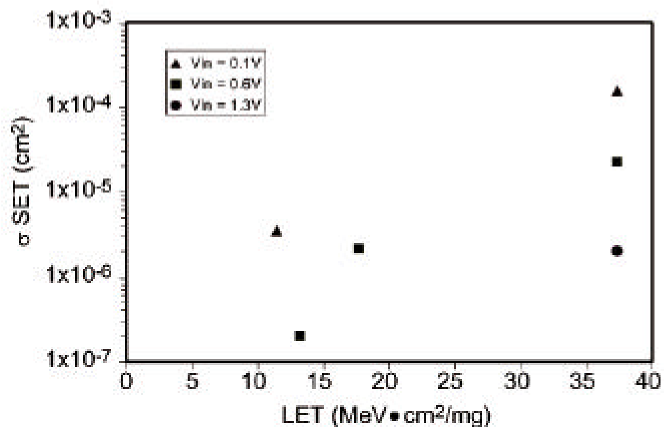

Figure 7. Mii42142 SET Cross Section for the indicated input voltages at $V_S$ = 15V.

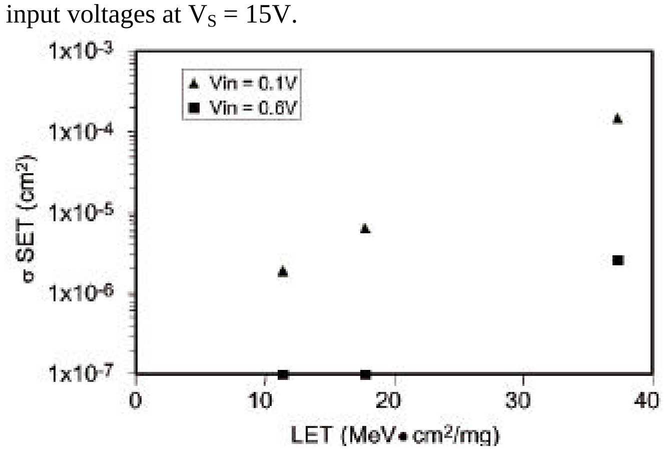

Figure 8: Mii42142 SET Cross Section for the indicated input voltages and $V_S$ = 8V.

*3) Mii53124 and Mii53253*

The Micropac Mii53124 ±90V/0.8A, and Mii53253 Dual 90V/0.8A power MOSFET optocoupler hybrids were irradiated with heavy ions at BNL to determine their susceptibilities to SET and other SEE. All devices showed some voltage fluctuations on the input that appeared to be precursors to SEGR. One Mii53124 device did have one current-based anomaly with the LED on. Cycling power reset the device. This anomaly occurred under irradiation with Br (LET = 37.3) and was not observed under any other conditions. All devices experienced SEGR, which caused the output voltage to drop significantly. Resetting the device did not return the device to functionality after SEGR. The onset of this effect occurred at 70V with LET = 60MeV•cm$^2$/mg for both device types. The device was deemed to have experienced a SET if the device switched on with the LED off. No SETs were observed for either device type. [22]

*4) Mii53250*

The Micropac Mii53250 40V/10A(2A) optocoupler hybrid solid-state relay was irradiated with heavy ions at BNL to determine device susceptibility to SET and SEE. The device was deemed to have experienced a SET if the device switched on with the LED off. This device showed no SET or SEGR to a fluence of 1x10$^7$ particles/cm$^2$ with LET = 60MeV•cm$^2$/mg at normal incidence and at 50° to the normal. The device was tested with $V_0$ = 40V and $I_0$ = 0.6A. This was deemed to be the worst-case condition as this represents the largest voltage drop from drain-to-source across the MOSFET. This device was also tested with the LED on to determine if there were any other effects; no anomalies were observed. [23]

*5) Mii53258*

The Micropac Mii 53258 120VDC/5A(2A) optocoupler hybrid solid-state relay was irradiated with heavy ions at BNL to determine its susceptibility to SET and other SEE. The device was deemed to have experienced a SET if the device switched on with the LED off. SEGR occurred in one device under irradiation with iodine ions (LET = 59.9) at normal incidence while the device was biased at 120V (the maximum rated voltage for the part) and $I_0$ = 0.2A. No SETs were observed in this device. The other devices showed no SET or SEGR to a fluence of 1x10$^7$particles/cm$^2$ with Br-81 (LET = 37 MeV•cm$^2$/mg) at normal incidence and 50° to the normal with $V_0$ = 60V and 120V. Nor were SET or SEGR observed for these devices under irradiation with I-127 (LET = 60 MeV•cm$^2$/mg) at normal incidence and 50° with $V_0$ = 60V with and $I_0$ = 0.2A in all cases. [23]

*6) HCPL6651*

The Agilent (Hewlett Packard) HCPL6651 (LDC0027) high-speed optocoupler was irradiated with 63MeV protons at UCD to determine the SET response of the device. The device was biased at $V_{CC}$ = 5V, $V_F$ = 5V, and $I_F$ was selectable via eight input resistors. During the testing the devices showed no significant CTR degradation to a fluence of 1.36x10$^{13}$p/cm$^2$.

The devices were tested for SETs with three output configurations: passive filter, active filter and no output filter. Four channels in each part were divided into two channels with no output filter and one channel each with passive and active filter. An SET was defined as an output deviation of ±0.5V from the expected value of the output sine wave. The device channels with the passive filter showed no transients on the output. The device channel with the active filter showed only a very few output transients with an angle of incidence effect and a cross section on the order of 10$^{-10}$cm$^2$ (Figure 9). The channels with no output filter showed a significant number of SETs with an angle of incidence effect and a maximum cross section of 5.4x10$^{-7}$cm$^2$ (Figure 10). [24] and [25]

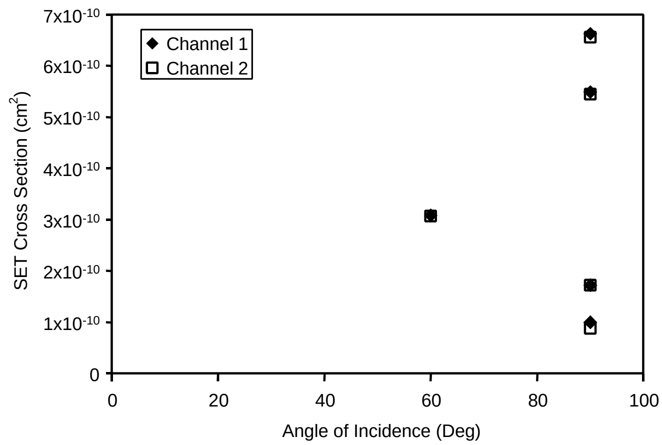


Figure 9. SET Cross Section vs. Angle of Incidence for the HCPL6651 with active SET filter (non-flight lot).

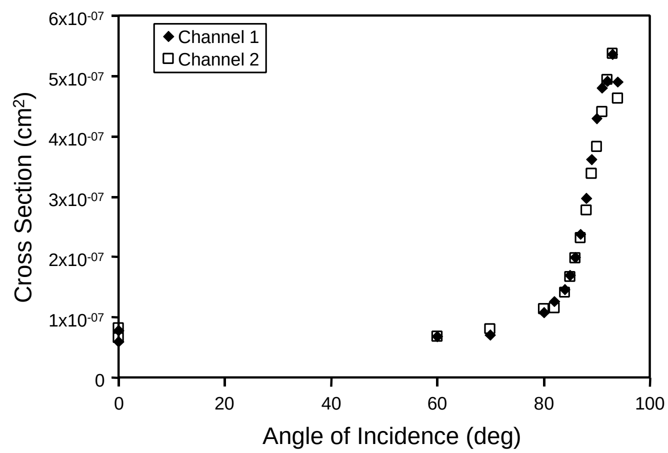


Figure 10. SET Cross Section vs. Angle of Incidence for the HCPL6651 with no SET filter (non-flight lot).

## V. Displacement Damage Test Results and Discussion

*1) OD800*

The OD800 LED from Optodiode was irradiated with 63MeV protons at UCD to determine the radiation induced degradation in the output of the device. The device is a GaAs double heterojunction LED. The mean ratio of post-irradiation power to pre-irradiation power, $P/P_0$, for all bias conditions was approximately 0.8 for a single exposure to 6x10$^{10}$p/cm$^2$. [26]

*2) P2824*

The Hamamatsu P2824 (manufactured 1997) optocoupler was irradiated with 63MeV protons at UCD to determine the CTR degradation of the device. The device was biased at $V_{CC}$ = 5V, $V_F$ = 5V, and $I_F$ was selectable via eight input resistors. There was some degradation in CTR at 1x10$^{10}$p/cm$^2$ and significant degradation was noted by the time a fluence of 4x10$^{10}$p/cm$^2$ was reached. No SETs were observed. [24]

*3) 66099*

The Micropac 66099 (LDC0048) optocoupler was irradiated with 63MeV protons at UCD to determine the CTR degradation of the device. The device was biased at $V_{CC}$ = 5V, $V_F$ = 5V, and $I_F$ was selectable via eight input resistors. The onset of CTR degradation occurred at 2.5x10$^{11}$ p/cm$^2$ and device performance was unacceptable at 7.5x10$^{11}$p/cm$^2$. No SETs were observed. [24]

*4) 4N49 and 4N49S*

The Micropac 4N49 (LDCs 9803 & 9819) was irradiated with 63MeV protons at UCD to determine the degradation of $V_{CE}$. No significant degradation in $V_{CE}$ was observed to a fluence of 5x10$^{11}$p/cm$^2$. Degradation was observed for the worst-case bias condition of $V_{CC}$ = 34V, $V_{IN}$ = 3.6V at 1x10$^{11}$p/cm$^2$.

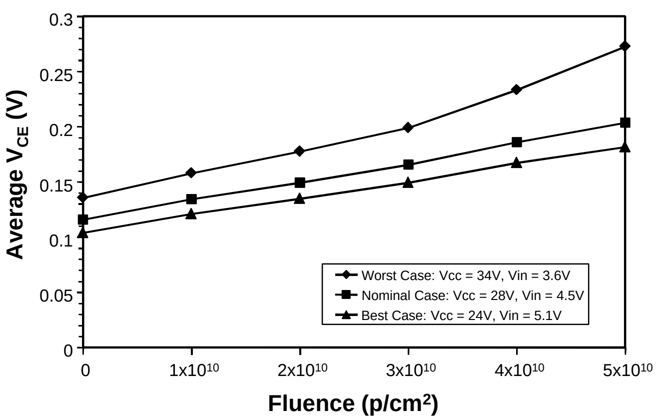

Figure 11. Micropac 4N49 (LDCs 9803 & 9819) average $V_{CE}$ results for the worst, nominal and best cases up to 5x10$^{10}$ p/cm$^2$ [27].

The Micropac 4N49 (LDC 0048) optocoupler was irradiated with 63MeV protons at UCD to determine the CTR degradation of the device. The device was biased at $V_{CC}$ = 5V, $V_F$ = 5V, and $I_F$ was selectable via eight input resistors. The onset of CTR degradation occurred at 5x10$^{10}$ p/cm$^2$ and device performance was unacceptable at 1.5x10$^{11}$ p/cm$^2$. No SETs were observed. [24]

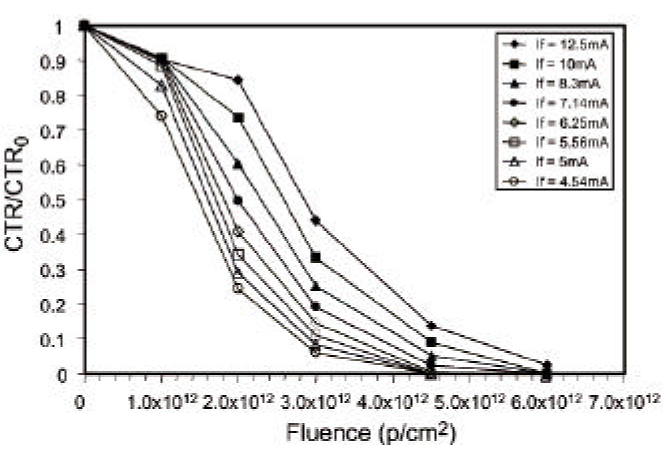

Figure 12. CTR degradation in 4N49S DUT 394 (Flight Lot)

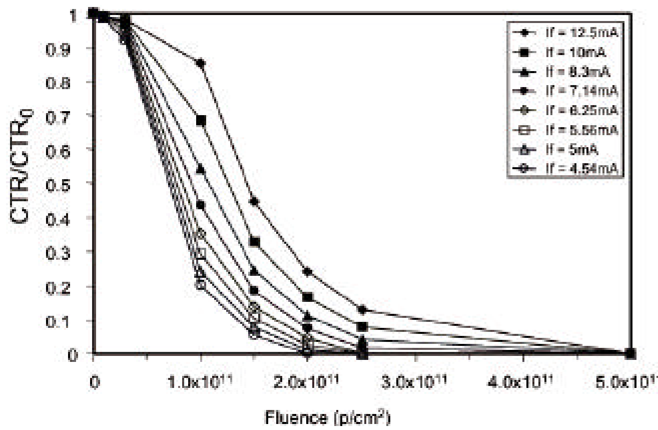

Figure 13. CTR degradation in 4N49 DUT 941 (Non-Flight Lot)

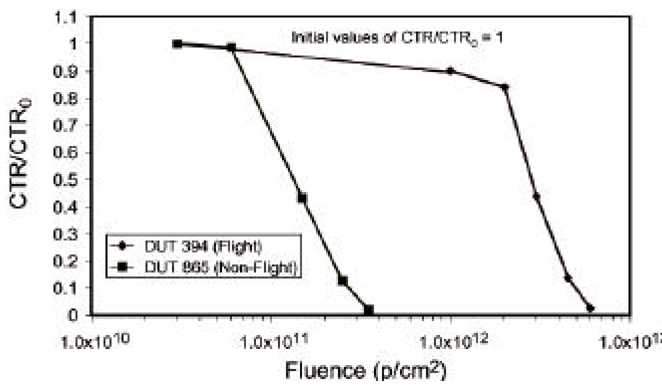

Figure 14. Comparison of 4N49 CTR degradation flight lot to non-flight lot for $I_F$=12.5mA. CTR$_0$ for DUT 394 = 0.623 (flight 4N49S), CTR$_0$ for DUT 865 = 0.586 (non-flight 4n49).

The Micropac 4N49S (LDC 9736) optocoupler was irradiated with 63MeV protons at UCD to determine the CTR degradation of the device. The device was biased at $V_{CC}$ = 5V, $V_F$ = 5V, and $I_F$ was selectable via eight input resistors. The onset of CTR degradation occurred at 1x10$^{12}$ p/cm$^2$ and device performance was unacceptable at 4.5x10$^{12}$ p/cm$^2$. No SETs were observed. [24]

*5) 6N134*

The Micropac 6N134 (66123) (LDC0046) high-speed optocoupler was irradiated with 63MeV protons at UCD to determine the CTR degradation of the device. The device was biased at $V_{CC}$ = 5V, $V_F$ = 5V, and $I_F$ was selectable via eight input resistors. The onset of CTR degradation occurred at 1.0x10$^{12}$ p/cm$^2$ and device performance was unacceptable at 3.0x10$^{12}$ p/cm$^2$. The SET test function did not operate correctly during testing, but SETs were expected. [24]

*6) 6N140*

The Micropac 6N140 (66124) (LDC9724) optocoupler was irradiated with 63MeV protons at UCD to determine the CTR degradation of the device. The device was biased at $V_{CC}$ = 5V, $V_F$ = 5V, and $I_F$ was selectable via eight input resistors. The onset of CTR degradation occurred at 7.5x10$^{11}$ p/cm$^2$ and device performance was unacceptable at 1.0x10$^{12}$ p/cm$^2$. No SETs were observed.

The Micropac 6N140 (66124) (LDC0048) optocoupler was irradiated with 63MeV protons at UCD to determine the CTR degradation of the device. The device was biased at $V_{CC}$ = 5V, $V_F$ = 5V, and $I_F$ was selectable via eight input resistors. The onset of CTR degradation occurred at $1.0x10^{12}$ p/cm$^2$ and device performance was unacceptable at $3.0x10^{12}$ p/cm$^2$. No SETs were observed. [24]

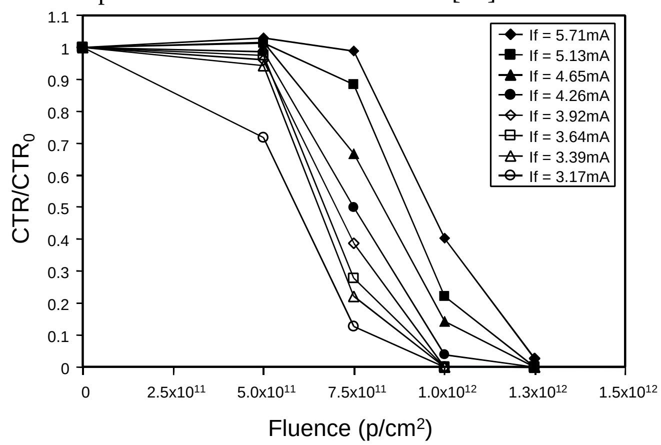


Figure 15. CTR Degradation in 6N140 DUT 597 Channel 1 (Flight Lot)

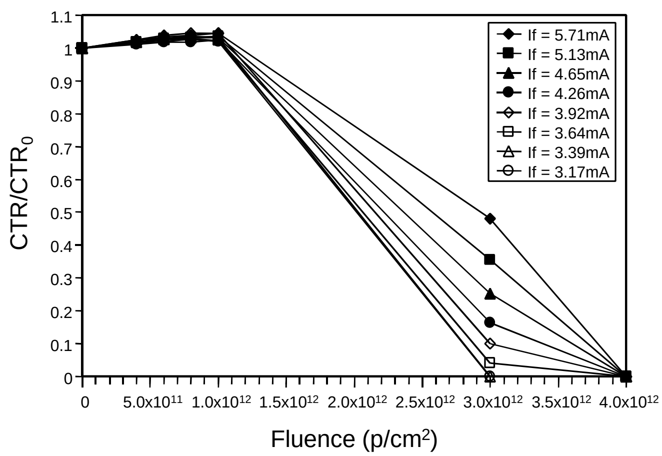


Figure 16. CTR Degradation in 6N140 DUT 286 Channel 1 (Non-Flight Lot)

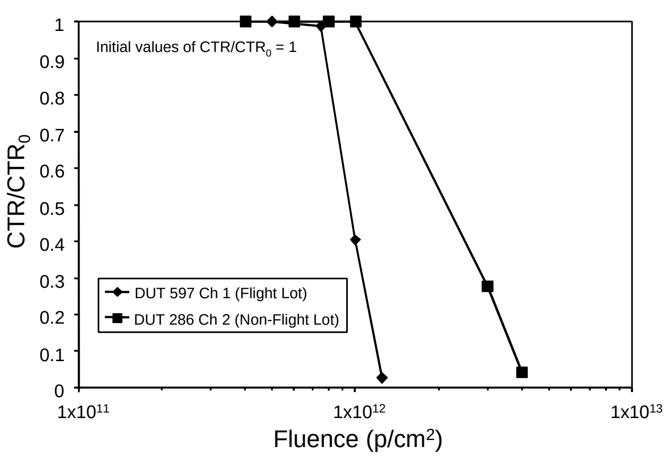


Figure 17. Comparison of 6N140 CTR degradation flight lot to non-flight lot for $I_F$=5.71mA

*7) Mii42142*

The Micropac Mii42142 power op amp was irradiated with 63MeV protons at UCD to determine device susceptibility to SET. The part showed no transients in its most sensitive configuration of $V_S$ = 8V and $V_{-IN}$ = 0.1V. The device also showed no loss of output current in the most stressful condition of $V_S$ = 15V and $V_{-IN}$ = 1.3V up to $3x10^{12}$ protons/cm$^2$ and only an 18.5% loss of output current after $7.44x10^{12}$ protons/cm$^2$. No SEGRs were observed. [21]

*8) Mii53124 and Mii53253*

The Micropac Mii 53124 ±90V/0.8A, and Mii53253 Dual 90V/0.8A power MOSFET optocoupler hybrids were irradiated with 63MeV protons at UCD to determine device susceptibility to SET. The DUTs showed no evidence of SET. There was a nominal increase in the forward current threshold for the LED but the threshold remained below the minimum specification limit for operating the devices. There was also no pronounced change in the output currents of the devices. Each DUT was tested to a total fluence of $1x10^{12}$ p/cm$^2$. [23]

*9) Mii53250 and Mii53258*

The Micropac Mii53250 40V/10A(2A) and Mii53258 120VDC/5A(2A) optocoupler hybrid solid-state relays were irradiated with 63MeV protons at UCD to determine their susceptibility to SET. The devices exhibited no SETs. There was a nominal increase in the forward current threshold for the LED, but threshold remained below the minimum specification limit for operating the device. There was also no pronounced change in the output current of the device. The devices were tested to a total fluence of $1x10^{12}$ p/cm$^2$. [22]

## VI. SEL Test Results and Discussion

### *A. Linear Bipolar Devices:*

*1) CMP402*

Heavy ion irradiations were conducted on the Analog Devices CMP402 comparator to ensure that they were not susceptible to SEL or any other SEE induced hard failure. No SELs were observed for a fluence of $1x10^7$ Iodine ions/cm$^2$ incident at 60$^o$ to the normal ($LET_{eff}$ = 119.8).

*2) OP16, OP37, and OP42*

Heavy ion irradiations were conducted on three Analog Devices op amps, OP42, OP37, and OP16, to ensure that they were not susceptible to SEL or any other SEE induced hard failure. All three parts survived irradiation to a fluence of $1x10^7$ ions/cm$^2$ of Br at normal incidence (LET=37).

### *B. ADC/DAC:*

*1) AD7535*

Heavy ion irradiations were conducted at BNL to determine the SEL sensitivity of the Analog Devices AD7535. No SELs were observed for a fluence of $1x10^7$ ions of Br incident at 60 to the normal ($LET_{eff}$ = 74.6).

*2) AD7564*

Heavy ion irradiations were conducted on the Analog Devices AD7564 comparator to ensure that they were not susceptible to SEL or any other SEE induced hard failure. No SELs were observed up to a fluence of $1x10^7$ Iodine ions/cm$^2$ incident at 60$^o$ to the normal ($LET_{eff}$ = 119.8).

*3) AD7664*

The Analog Devices AD7664 ADC was tested for SEU and SEL at BNL using ions with LETs ranging from 7.88 (Si) to 37.9 (Br). The ADCs were tested under the bias conditions of + 5 V.

Testing was performed to determine the latchup threshold LET. Both devices tested showed the same threshold characteristics with an LET threshold of 8-10 MeV•cm$^2$/mg. For all test conditions, the DUTs were exposed to the ion beam until latchup occurred. At this point the fluence was recorded. Typically, 2 to 3 fluence readings were taken for each test condition to allow for some statistics in calculating a cross section. This cross section data is shown in Figure 18.

Consider the cross section data in Figure 18. SEL did not occur for 5 x $10^6$ ions/cm$^2$ of Si at normal incidence (LET=7.88). The data point with the downward arrows for this LET value thus represent upper limits for the SEL cross section. SEL did occur for Si incident at 30$^o$ (LET=9.1), indicating an SEL threshold LET between these two values. Despite the considerable spread in the cross section data, the "best fit" curve through the data yields a reasonable estimate of the saturation cross section, $\sigma_{sat} \cong$ 2 to 3 x $10^{-4}$ cm$^2$.

It should be noted that for $LET_{th}$ of 10 or less, the possibility of sensitivity to proton-induced events exists. This possibility is not addressed by this testing. [28]

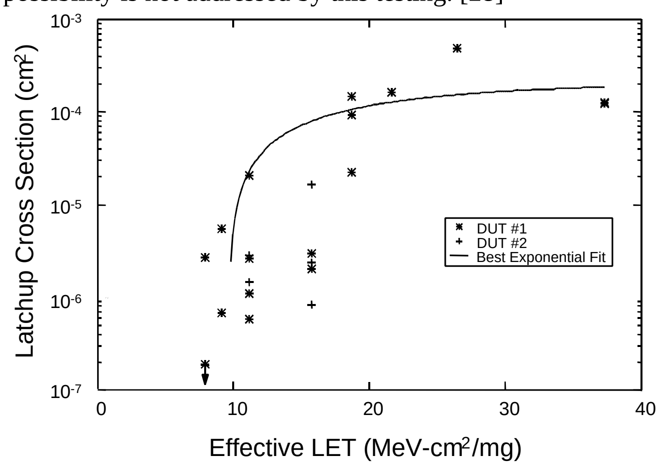


Figure 18. The symbols show the cross section data as a function of Effective LET for the two DUTs. Note: Symbols with a downward arrow indicate that no SEL occurred for that LET.

*4) AD7854*

The Analog Devices AD7854 is a CMOS single-channel, 200 kbps 12 bit ADC. It was tested for SEL only and found to be susceptible to SEL with a threshold LET between 8 and 11 MeV•cm$^2$/mg and with a limiting cross section between $1x10^{-4}$ and $1x10^{-3}$ cm$^2$. The device was susceptible for both 3.6 and 5 volt supply voltages. [29]

*5) AD7858*

The Analog Devices AD7858 is a CMOS 8 channel, 200 kbps 12 bit ADC. It was tested for SEL only and found to be susceptible with a threshold LET between 11 and 22 MeV•cm$^2$/mg and a limiting cross section between $1x10^{-4}$ and $1x10^{-3}$ cm$^2$. The device was susceptible for both 3.6 and 5 volt supply voltages. [30]

*6) AD7888*

The Analog Devices AD7888 is a CMOS 8 channel, 125 kbps 12 bit ADC. It was tested for SEL only and found to be susceptible with a threshold LET between 16 and 22 and a limiting cross section between $1x10^{-5}$ and $1x10^{-4}$ cm$^2$. The device was susceptible for both 3.6 and 5 volt supply voltages. [31]

*C. Miscellaneous:*

*1) ADG704*

The Analog Devices ADG704 is a low-voltage (1.8 to 5 V) quad CMOS multiplexer. It was tested for SEL only and found to be susceptible with a threshold LET of about 16 and with a limiting cross section between $1x10^{-5}$ and $1x10^{-4}$ cm$^2$. The device was tested only at the upper limit of its supply voltage range. [32]

*2) AMP01*

The AMP01 was tested to further characterize a destructive failure observed in 1998 SEE tests [5]. The new tests raised the lower limit on the LET threshold for failure to >32.7 ($1x10^7$ ions/cm$^2$ of Ge at normal incidence). No dependence on temperature or device load were observed. The higher threshold LET and the fact that failure is more likely for normally incident ions imply that the failure rate for this mechanism will be low – for example, less than $1x10^{-10}$ failures per day per device in geostationary orbit. [5].

*3) INA117*

The Texas Instruments/Burr-Brown INA117 is a differential amplifier. It was tested for SEL and other destructive mechanisms only. No destructive events were observed for an effective fluence of $1x10^7$ ions/cm$^2$ of Iodine incident at 60 degrees for an effective LET of 119.9.

*4) MAX313*

Testing was performed at BNL to determine the SEL susceptibility of the Maxim MAX313 Analog Switch. Supply current was monitored for an increase or decrease. No SELs were observed for the MAX313 up to a fluence of $1x10^7$ ions/cm$^2$ of iodine at normal incidence (LET=59.8). [33]

*5) MAX4503*

The Maxim MAX4503 CMOS switch was tested for SEL susceptibility at BNL. Test conditions included the supply voltage set to 3.6 V, the DC input to the switch of 2.15 V. The switching voltage set to 3.3 V and the frequency was 200 Hz. No SELs were observed up to LET of 37. At LET values of 37 and greater, transients on the output were beginning to appear. As this was only a latchup test, details of the transients were not investigated. However, with an LET threshold of 37, the event rate should be very small. [34]

### 6) *MAX4528 and MAX4583*

SEL sensitivity tests were preformed at BNL on the Maxim MAX4528 and MAX 4583 CMOS analog switches. The power supply current was monitored for large increases and the device functionality was verified after each SEL.

The MAX4528 exhibited no SEL events up to a fluence of $1x10^7$ ions/cm$^2$ of iodine (LET=59.9). The MAX4583 exhibited no SEL events for a fluence of $1x10^7$ ions/cm$^2$ of iodine incident at $60^o$ ($LET_{eff}$=119.8). [35]

### 7) *MAX4617*

The Maxim MAX4617 CMOS analog multiplexer was tested at BNL for sensitivity of SEL. The power supply was monitored for large increases. The MAX4617 exhibited no SEL events for a fluence of $1x10^7$ ions/cm$^2$ of iodine incident at $60^o$ ($LET_{eff}$=119.8). [36]

### 8) *MAX584*

Testing was performed at BNL to determine the SEL susceptibility of the Maxim MAX584 voltage reference. No SELs were observed up to a fluence of $1x10^7$ ions/cm$^2$ of Br at normal incidence ($LET_{eff}$=37.3).

## VII. SUMMARY

We have presented recent data from SEE, and proton-induced damage tests on a variety of mainly commercial devices. It is the authors' recommendation that this data be used with caution. We also highly recommend that lot testing be performed on any suspect or commercial device.

## VIII. ACKNOWLEDGMENT

The Authors would like to acknowledge the sponsors of this effort: NASA Electronics Radiation Characterization (ERC) Project, a portion of NASA Electronic Parts and Packaging Program (NEPP), NASA Flight Projects, and the Defense Threat Reduction Agency (DTRA) under IACRO 01-4050/0001278.

## IX. REFERENCES

[1] NASA/GSFC Radiation Effects and Analysis home page, http://radhome.gsfc.nasa.gov

[2] K. LaBel, private communication, May 2001.

[3] C Poivey, et al., "Development of a Test Methodology for Single Event Transients (SETs) in Linear Devices," submitted and accepted for publication in 2001 IEEE Radiation Effects Data Workshop, July, 2001, PH-2.

[4] J.W. Howard, et al., "Total Dose and Single Event Effects Testing of the Intel Pentium III (P3) and AMD K7 Microprocessors," submitted and accepted for publication in 2001 IEEE Radiation Effects Data Workshop, July, 2001, W-7.

[5] M.V. O'Bryan, et al., "Recent Radiation Damage and Single Event Effect Results for Microelectronics," NSREC99 Data Workshop, 1-14, July 1999.

[6] Jim Howard, et al., "Single Event Upset and Latchup Testing of the AD1674 Analog Devices Analog to Digital Converter," http://radhome.gsfc.nasa.gov/radhome/papers/B080100.pdf, August 2000.

[7] Jim Howard, et al., "Single Event Upset and Latchup Testing of the AD6640 Analog Devices Analog to Digital Converter," http://radhome.gsfc.nasa.gov/radhome/papers/B111600a.pdf, November 2000.

[8] R. A. Reed, et al., "Proton-Induced Single Event Upset Characterization of a 1 Giga-Sample per Second Analog to Digital Converter," Fifth European Conf. Radiation Effects on Components and Systems, RADECS 99, 188-192, September 1999.

[9] Jim Howard, et al., "Single Event Transient and Destructive Single Event Effects Testing of the AFL12005SX/CH Advanced Analog Lambda, Inc. DC/DC Converters," http://radhome.gsfc.nasa.gov/radhome/papers/B080100a.pdf, August 2000.

[10] Jim Howard, et al., "Single Event Transient and Destructive Single Event Effects Testing of the AFL12012DX/CH Advanced Analog Lambda, Inc. DC/DC Converters," http://radhome.gsfc.nasa.gov/radhome/papers/B080100b.pdf, August 2000.

[11] Jim Howard, et al., "Single Event Transient and Destructive Single Event Effects Testing of the AFL12015DX/CH Advanced Analog Lambda, Inc. DC/DC Converters," http://radhome.gsfc.nasa.gov/radhome/papers/B080100c.pdf, August 2000.

[12] Jim Howard, et al., "Single Event Transient and Destructive Single Event Effects Testing of the DVHF2803R3SF/HBM VPT, Inc. DC/DC Converters," http://radhome.gsfc.nasa.gov/radhome/papers/B111500a.pdf, November 2000.

[13] Jim Howard, et al., "Single Event Transient and Latchup Testing of the LCM-120 Interpoint Line Conditioning Module," http://radhome.gsfc.nasa.gov/radhome/papers/B080100d.pdf, August 2000.

[14] A. Sanders, "Total Ionizing Dose (TID) Test Report, Version 1.0 Interpoint Line Conditioning Module (LCM) LCM-120 SN0025 T0003 LCM-120 SN0011 T9952 Tested 5/22/00-5/27/00," http://radhome.gsfc.nasa.gov/radhome/papers/G052200.pdf, July 2000.

[15] Jim Howard, et al., "Single Event Transient and Destructive Single Event Effects Testing of the MDI3051RES05ZF Modular Devices, Inc. DC/DC Converters", http://radhome.gsfc.nasa.gov/radhome/papers/B080100e.pdf, August 2000.

[16] Jim Howard, et al., "Single Event Transient and Destructive Single Event Effects Testing of the MDI3051RES12ZF Modular Devices, Inc. DC/DC Converters," http://radhome.gsfc.nasa.gov/radhome/papers/B080100f.pdf, August 2000.

[17] Jim Howard, et al., "Single Event Transient and Destructive Single Event Effects Testing of the MDI3051RES15ZF Modular Devices, Inc. DC/DC Converters," http://radhome.gsfc.nasa.gov/radhome/papers/B080100g.pdf, August 2000.

[18] S. Kniffin et al., "Heavy Ion and Proton Single Event Effects Test Results for the Fairchild LM148 Quad Op Amp," http://radhome.gsfc.nasa.gov/radhome/papers/D082400.pdf, October 2000.

[19] Jim Howard, et al., "Proton Dose and Single Event Effects Testing of the Intel Pentium III (P3) and AMD K7 Microprocessors," http://radhome.gsfc.nasa.gov/radhome/papers/i062100.pdf, June 2000.

[20] Robert Reed and Hak Kim, "Heavy Ion Single Event Effects Test Results for the NonVolatile Electronics IL710 Isolator",

http://radhome.gsfc.nasa.gov/radhome/papers/B092600.pdf, September, 2000.
[21] S. Kniffin et al., "Heavy Ion Single Event Effects Test Results for the Micropac Mii42142 Power Operational Amplifier," http://radhome.gsfc.nasa.gov/radhome/papers/D120400c.pdf, September, 2000.
[22] S. Kniffin et al., "Heavy-Ion and Proton Test Results for the Micropac Mii53124 and Mii53253 Power MOSFET Optocouplers," http://radhome.gsfc.nasa.gov/radhome/papers/D120400e.pdf, September, 2000.
[23] S. Kniffin et al., "Heavy Ion Single Event Effects Test Results for the Micropac Mii53250 and Mii53258 Optocoupler-Based Solid State Relays," http://radhome.gsfc.nasa.gov/radhome/papers/D120400d.pdf, September, 2000.
[24] S. Kniffin et al., "Test Report for STRV-1d Ground Data Taken at UC Davis," http://radhome.gsfc.nasa.gov/radhome/papers/D120400a.pdf, December 2000.
[25] R.A. Reed, C.J. Marshall, J.L. Barth, K.A. LaBel, C. Poivey, P.W. Marshall, S. Kniffin, C. Seidleck, "Assessing the Impact of the Space Radiation Environment on Parametric Degradation and Single Event Transients in Optocouplers," submitted and accepted for publication in 2000 IEEE Radiation Effects Data Workshop, July, 2001, PH-5.
[26] S. Kniffin et al., "Proton Effects Test Results for the Optodiode OD800 Light Emitting Diode," http://radhome.gsfc.nasa.gov/radhome/papers/D080700.pdf, August 2000.
[27] S. Kniffin et al., "Report for VCE Degradation in Mii 4N49 Optocouplers for IRAC," http://radhome.gsfc.nasa.gov/radhome/papers/D120400b, December 2000.
[28] Jim Howard and Jim Fourney, "Single Event Latchup Testing of the AD7664 Analog Devices Analog to Digital Converter," http://radhome.gsfc.nasa.gov/radhome/papers/B030600.pdf, March 2000.
[29] Ray Ladbury, et al., "Heavy Ion Latch-up Test Results for the Analog Devices AD7854 ADC," http://radhome.gsfc.nasa.gov/radhome/papers/B092500a.pdf, September 2000.
[30] Ray Ladbury, et al., "Heavy Ion Latch-up Test Results for the Analog Devices AD7858 ADC," http://radhome.gsfc.nasa.gov/radhome/papers/B092500b.pdf, September 2000.
[31] Ray Ladbury, et al., "Heavy Ion Latch-up Test Results for the Analog Devices AD7888 ADC," http://radhome.gsfc.nasa.gov/radhome/papers/B092500c.pdf, September 2000
[32] Ray Ladbury, et al., "Heavy Ion Latch-up Test Results for the Analog Devices ADG704 Multiplexer," http://radhome.gsfc.nasa.gov/radhome/papers/B092700b.pdf, September 2000.
[33] Jim Howard, et al., "Heavy Ion Single Event Transient (SET) and Latchup (SEL) Test Results for the Maxim Analog Switch (MAX313MTE)," http://radhome.gsfc.nasa.gov/radhome/papers/B080100h.pdf, August 2000.
[34] Jim Howard, et al., "Heavy Ion Single Event Latchup (SEL) Test Results for the Maxim CMOS Switch (MAX4503)," http://radhome.gsfc.nasa.gov/radhome/papers/B111600c.pdf, November 2000.
[35] Ray Ladbury, et al., "Heavy Ion Latch-up Test Results for the Maxim MAX4528, MAX4583 CMOS Analog Switches," http://radhome.gsfc.nasa.gov/radhome/papers/B092700c.pdf, September 2000.
[36] Ray Ladbury, et al., "Heavy Ion Latch-up Test Results for the Maxim MAX4617 CMOS Analog Multiplexer," http://radhome.gsfc.nasa.gov/radhome/papers/B111700.pdf, November 2000.